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Distributed Situation Awareness in Dynamic Systems: Theoretical Development and Application of an Ergonomics Methodology

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Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology

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The purpose of this paper is to propose foundations for a theory of situation awareness based on the analysis of interactions between agents (i.e. both human and non-human) in subsystems. This approach may help to promote a better understanding of technology-mediated interaction in systems, as well as helping in the formulation of hypotheses and predictions concerning distributed situation awareness. It is proposed that agents within a system each hold their own situation awareness, which may be very different from (although compatible with) that of other agents. It is argued that we should not always hope for, or indeed want, sharing of this awareness, as different system agents have different purposes. This view marks situation awareness as a dynamic and collaborative process binding agents together on tasks on a moment-by-moment basis. Implications of this viewpoint for the development of a new theory of, and accompanying methodology for, distributed situation awareness are offered.

Keywords: Agents; Systems theory; Command and control; Situation awareness; Teams

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1. Introduction

In this paper we present a description of distributed situation awareness (DSA) which is system oriented, rather than individual oriented. We argue that this approach provides us with a means of examining situation awareness (SA) in team working. Our aim is to develop measures of DSA that can support prediction of performance and inform the interpretation of observations made in the field (e.g. in terms of explaining possible mistakes, or of comparison of command and control across different organizations). Researchers such as Hollnagel (1993) and Hancock (1997) have made convincing arguments for the system's perspective in analysing human–machine interaction. The hierarchical and heterarchical relationships and interactions between structures and functions at different levels have certainly served human factors researchers well in the past (Rasmussen 1986, Meister 1989, Singleton 1989, Wilson and Corlett 1995, Salvendy 1997, Vicente 1999). In a review of contemporary team teamwork research, Paris *et al.* (2000) found that most theories, models, and taxonomies comprise a tripartite input–process–output approach from general systems theory. This seems to be a useful distinction for the development of a predictive model. Indeed, the systems theoretic approach would enable different levels of description appropriate to the nature of the prediction being offered. The systems framework offers the possibility of analysing interactions and relationships at many different levels and focusing of specific interactions within subsystems. Researchers have suggested that technical aspects of the system are part of the joint cognitive system (Hollnagel 1993). Research into trust and technology suggests that there are shared traits between interpersonal trust and technological trust (Muir 1994, Muir and Moray 1996). Ashleigh and Stanton (2001) have shown that those shared traits included emotive constructs (i.e. confidence, respect, commitment, and teamwork), cognitive constructs (e.g. understanding, ability, and expectancy), and behavioural constructs (e.g. reliability, performance, and communication). The authors report that the people they interviewed did not distinguish between human and non-human agents when using these constructs. The idea of collaborative human and non-human SA agents seems to be a useful concept to carry forward into our theory.

We assume that, in distributed team work, cognitive processes occur at a systems rather than an individual level. Thus if we take Endsley's (1995) three-stage model of SA (perception–comprehension–projection, which maps directly onto the tripartite input-process-output systems approach), it is possible to apply this to a 'system' as shown in table 1. In this example, a handheld gas analyser is used to determine whether fumes from a chemical are at risky levels. Once a threshold has been exceeded, the fire-fighter carrying the device decides to evacuate the area. The incident commander, watching the fire-fighter, realizes that there is a risk and orders the crew to return to their vehicles.

This is quite a simple example as it is linear—output from the gas analyser is input for the fire-fighter and, to a certain extent, the fire-fighter's output is the commander's input—but it serves to illustrate two factors that are important to the approach developed in this paper. First, the 'knowledge' that underlies DSA is distributed across the system. Secondly, there is implicit communication of information rather than detailed exchange of mental models. From the example in table 1, we can claim that the gas analyser represents its readings through a display showing that thresholds have been exceeded. Thus, as some of the significant factors that will influence individual cognitive performance will involve the representation, transformation, and manipulation of information, i.e. from perception to cognition to action, so too can the systems-level model address such factors. Indeed, much of the work on distributed cognition

Table 1. DSA in part of a fire-fighting system.

Agent	Perception	Comprehension	Projection
Gas analyser	Senses level of toxic gas	Calculates current gas level and compares against threshold	Indicates that gas level could be hazardous to health if exposure prolonged
Fire-fighter 1	Reads level on meter	Determines high level equates to risk to self	Need to exit building
Incident commander	Sees fire-fighter pause in doorway	Decides gas level presents risk to crew	Switch to defensive response

(Hutchins 1991, 1995, Flor and Hutchins 1991, Perry 2003) has specifically addressed the questions of representation, particularly in terms of the ways in which artefacts (and their use by people) can be used to represent information in ways that can support the 'immediate' extraction of meaning by people (cf. the theory of affordances (Norman 1988)), or can be used to embed complex manipulations into simple actions. It must be emphasized at this point that the approach takes a systems view, rather than looking at individuals. Therefore current conceptions of DSA do not take individual variables into account. There are theories of SA that already do this very well, and the purpose of this paper is to focus attention at a higher level in the system. This does not mean that individual SA is dismissed; rather, a systems analysis cannot be accounted for by summing independent individual analyses.

These fundamental ideas of SA distributed in a system lead us to propose a set of tenets that could form the basis of a theory (Stanton *et al.* 2004a). These propositions are as follows.

1. SA is held by human and non-human agents. As table 1 shows, technological artefacts (as well as human operators) have some level of situation awareness (at least in the sense that they are holders of contextually relevant information), in this case the presence of toxic gas.
2. Different agents have different views on the same scene. As table 1 shows, the gas analyser, fire-fighter and incident commander all have different views on the scene, as illustrated in their perception, comprehension, and projection of the incident.
3. Whether or not one agent's SA overlaps with that of another depends on their respective goals. Although they are part of the same fire-fighting system, the goal of the gas analyser is to detect the level of toxic gas in the environment, the goal of the fire-fighter is to determine the level of risk present in the environment, and the goal of the incident commander is to decide on the appropriate response for his/her crew. In terms of Endsley's model of SA ,it could be that the different agents are actually representing different stages of SA, rather than being microcosms of SA themselves—the gas analyser perceives, the fire-fighter comprehends, and the incident commander projects.
4. Communication between agents may be non-verbal behaviour, customs, and practice (but this may pose problems for non-native system users). For example, the incident commander takes the pause by the fire-fighter in the doorway as a signal that there is something wrong.
5. SA holds loosely coupled systems together. The relationship between the gas analyser, fire-fighter, and incident commander is held together by the by their

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respective levels or stages of awareness of the presence of toxins in the environments and the most appropriate response.

6. One agent may compensate for degradation in SA in another agent. For example, one fire-fighter may be unaware of the level of toxins in the environment until he/she is informed by the gas analyser, another fire-fighter, or the incident commander.

The types of incident that we are exploring can be considered in terms of Klein's (1989) notions of naturalistic decision-making, i.e. agents in the field are able to draw upon their experience and expertise to make rapid diagnosis and to perform effective actions in very limited timeframes. In a similar fashion, Smith and Hancock (1995, p. 59) propose that 'SA is the up-to-the minute comprehension of task relevant information that enables appropriate decision making under stress'. As our theory of SA operates at a systems level, it has a different perspective on the individual and shared SA approaches. We feel that the shared SA approach could misdirect attention to inappropriate aspects of the task, whereas there are points in tasks where SA may overlap for brief periods in distributed team working. However, distributed SA requirements are not the same as shared SA requirements. Shared SA implies shared requirements and purposes, whereas distributed SA implies different, but potentially compatible, requirements and purposes.

Therefore our approach assumes that DSA can be defined as activated knowledge for a specific task within a system. This echoes the notion of Bell and Lyon (2000, p. 142) that 'SA could be defined as knowledge (in working memory) about elements of the environment'. Therefore taking this notion into the realm of distributed cognition allows us to propose that a situation requires the use of appropriate knowledge (held by individuals, captured by devices, etc.) which relates to the state of the environment and the changes as the situation develops. For the model presented in this paper, the 'ownership' of this knowledge is initially at the system rather than the individual level. This notion could be further extended to include 'meta-SA', where knowledge of other agents' knowledge is contained in the system, such that each agent could potentially know where to go when they need to find something out.

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2. Case study on Type 23 frigate operations control room at HMS Dryad

In order to apply the ideas of DSA to command and control, we have spent time at HMS Dryad (which is the headquarters of the Royal Naval School of Maritime Operations, where there are a number of land-based operations control room simulators) collecting data on anti-air warfare, surface, and subsurface threat tasks. The Event Analysis of Systemic Teamwork (EAST) methodology (see Walker *et al.* (2006) for a more in-depth discussion of the approach) takes data from hierarchical task analysis (HTA) (Annett 2005) (Annett *et al.* (2000) have demonstrated how HTA can be used to capture the principle components of teamwork in an anti-submarine warfare task), direct observation of tasks, and debriefing interviews using the critical decision method (Klein and Armstrong 2005) to produce three main representations of a system: a social network, a task network, and a knowledge network. We believe that these networks offer different, but compatible, facets of systems representation. At the highest level of representation the social network represents communication relations between people in the system (Houghton *et al.* 2006). In the interests of brevity, this representation will not be shown in the current paper. At the next level down, the task network shows the relationship between goals of different agents in the system. At the lowest level of representation is the knowledge network, which shows the relationship between classes of information that the system knows about in order to perform effectively.

For the purposes of the HMS Dryad Type 23 frigate operations control room studies, an observer was able to sit directly behind a crew member and to plug into his/her console, allowing all radio exchanges to be heard. The anti-air warfare officer (AAWO) was observed during the air threat, and the principal warfare officer (PWO) was observed during the subsurface and surface threats. All forms of communication were recorded, including verbal exchanges not communicated via radio, hand gestures, and written communication (on paper). Figure 1 shows part of the Type 23 operations room.

Within these scenarios there are four main agents: the officer of the watch (OOW), the PWO, the AAWO, and the captain. The OOW is an officer on the ship's bridge who maintains the visual lookout and controls the ship. The OOW can overrule the manoeuvring orders from the operations room if he/she considers them to be dangerous. The PWO is responsible for the tactical handling of the ship and the integrated use of its weapons systems and sensors. The PWO takes a tactical command role in multi-threat missions. The AAWO is responsible for the plan of defence in response to an air attack. The captain oversees the operations room. In addition to personnel, the ship has a computer-based command system which can communicate and control weapons and sensor systems which allow information to be passed independently of the command system itself. An illustration of the seating layout and an accompanying glossary are given in figure 2 and table 2, respectively.

Originally, the primary task of Type 23 frigates was anti-submarine warfare. More recently, their role includes air and surface warfare. All three scenarios fit into similar task models. In order to manage this scenario, a number of goals need to be addressed: plan resources and strategy, control external resources, posture platform for attack, identify and classify targets, assess threat and allocate targets, engage targets, and re-allocate assets and weapons.

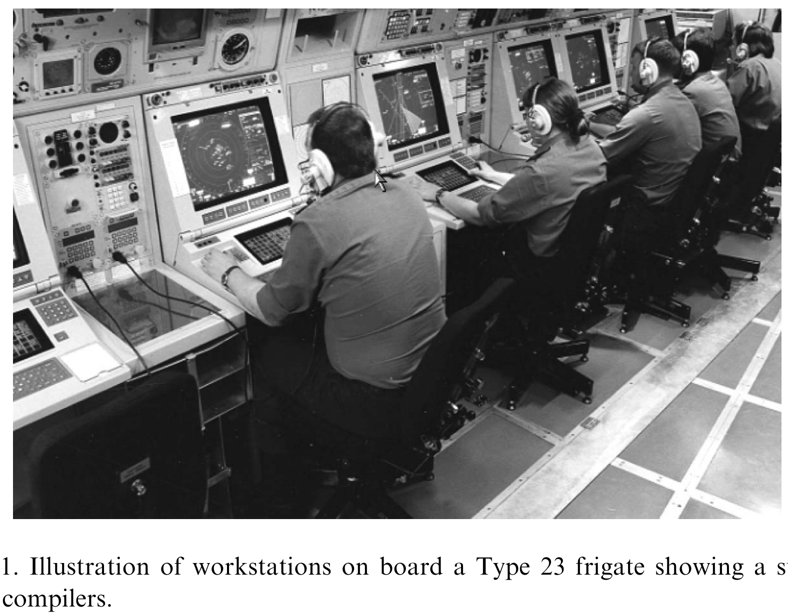

Figure 1. Illustration of workstations on board a Type 23 frigate showing a subset of picture compilers.

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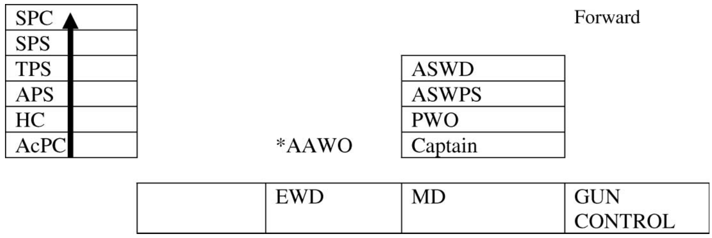

Figure 2. Seating layout of a Type 23 frigate operations room. The asterisk denotes where the AAWO is standing.

Table 2. The main agents involved in the mission.

Agent (title or acronym)	Explanation of acronym
Captain	
PWO	Principal warfare officer
AAWO	Anti-air warfare officer
ASWPS	Anti-submarine picture supervisor
SPC	Surface picture controller
EWD	Electronic warfare director
MD	Missile director
HC	Helicopter controller
APS	Air picture supervisor
Off Ship	Other ships, aircraft, etc
Duty Staff	
OOW	Officer of the watch
ASWD	Anti-submarine warfare director
ASW	Anti-submarine warfare officer
SPS/Surface	Surface picture supervisor
Harpoon	
CY	Communication yeoman
AcPS	Action picture supervisor

The task model shown in figure 3 illustrates the relationship between these goals. Before the mission, the planning of resources and strategy is undertaken. During the mission the central tasks are performed concurrently by different parts of the team. New targets are identified and classified by the picture compilers and picture supervisors. The targets are then assessed and prioritized by the AAWO and PWO, who allocate assets and weapon systems to the high-priority threats. The targets are then engaged by the assets and weapon systems as appropriate, and the degree of success is assessed. Successfully damaging or deterring a target frees up the asset or weapon system for new allocation. Missed targets may require re-allocation. At the same time as all this activity is being undertaken, the platform is being postured to optimize the engagement or the ability to evade enemy weapons. There is also a requirement to coordinate with other platforms and control other external resources (such as fighters and helicopters). Thus the whole operation demands considerable coordination of both internal (to the platform) and external resources and assets to manage a mission and deal with threats.

The majority of communications on board the Type 23 frigate are verbal, via the radio circuits. The PWO and AAWO have access to 20 external circuits, of which there are four

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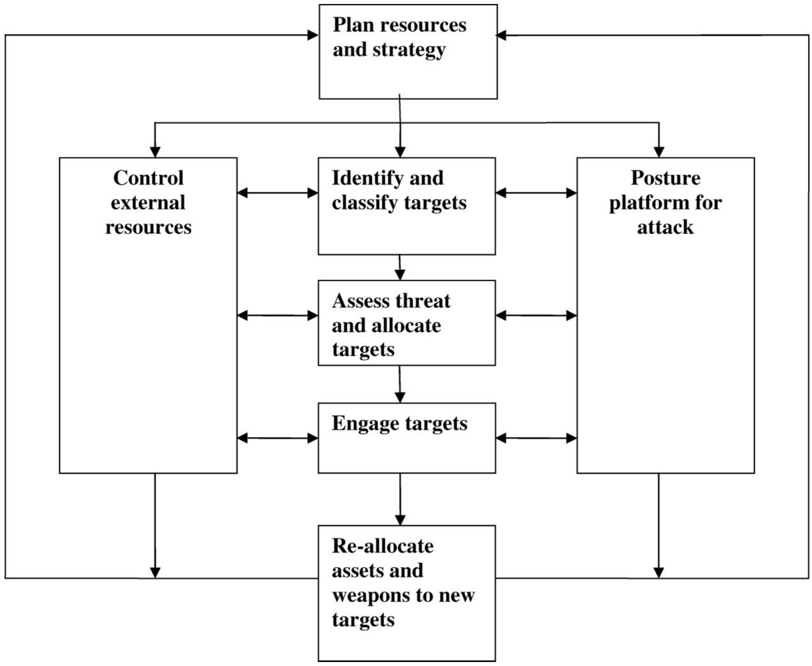

Figure 3. Illustration of the task network representation for a Type 23 frigate.

major nets. Internally there is one main 'open line' with up to 40 point-to-point interphones. This method of communication has interesting implications for DSA, and has proven advantages in other areas (e.g. air traffic control). Although the personnel sit side-by-side, they communicate via headsets and microphones, and their visual attention is focused on the displays in front of them. For some tasks there may only be marginal advantage to be gained by the physical co-location of the team members, as noted by Stanton *et al.* (2002). However, the common battle-space picture is built on the status displays and screens in front of the AWO and PWO. This makes co-location of these roles extremely important for a coordinated response. The subsurface and surface battles are usually fought over one net, while the air battle is fought over another. The command open line is used by the captain, AAWO, PWO, OOW, ASW Director, Duty Staff, EW director, missile and gun director, and communications yeoman, and on a part-time basis by the helicopter controller. In addition to these radio channels, crew members speak face to face and use hand-written notes. Pointing to the screens when matters need to be clarified was also observed.

The deepest level of analysis and representation provided is the knowledge network, which describes the tasks that the system has to attend to in different phases of activity. The task network will be used to frame the knowledge network, in order to show the knowledge network relevant to different goals of the system. One of the advantages of defining network models is that it is possible to consider the potential effects of changes in those networks. For example, what would be the effects of changing the task, social, or propositional networks? Would DSA be improved, remain the same, or be adversely affected? Similar questions could be proposed with respect to mission effectiveness, workload, error rates, and timeliness of the systems response. However, our initial studies

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have focused on the modelling of contemporary system networks, as illustrated in the next section.

3. DSA methodology

The DSA methodology comprises three main parts. In the first part, the knowledge owned by each party in each phase of the operation is elicited. The critical decision method (CDM) has been used for this task. The second part is to extract 'knowledge objects' from the CDM. Content analysis has been used for this task. The third and final part is to represent the relations between knowledge objects and identify in which phase(s) they are activated. Propositional networks, comprising 'subject', 'relation', and 'object' network structures of the knowledge required by the system to describe any given situation, were used for this task. Further details of the procedure and examples of the results are given below.

3.1. *Elicit the knowledge owned by each party*

Flanagan (1954) developed an interviewing protocol which allowed him to investigate 'critical incidents' in aviation. The technique employs a semi-structured interview to elicit key factors in accounts of incidents. In Flanagan's approach, the method was used as a vehicle for interviewing groups of respondents (as opposed to individuals). The interview could commence with a broad question, such as: 'Can you think of any incident or near-miss or event which happened to you, or a colleague, which could have resulted in an accident, given other circumstances?' (Kirwan 1994, p. 66). The idea is that respondents produce accounts of incidents which can then be discussed.

In recent years, the study of decision-making in real-world situations has received a great deal of attention. While much of the work involves observation, there is also an emphasis on the use of interviews to collect information. The critical decision method (Klein 1989) is a form of critical incident technique. According to Klein (1989, p. 464), 'The CDM is a retrospective interview strategy that applies a set of cognitive probes to actual non-routine incidents that required expert judgment or decision making'. In this approach, the interview proceeds through a series of four stages: briefing and initial recall of incidents, identifying decision points in a specific incident, probing the decision points, and checking.

The CDM makes use of information provided during observation of a scenario and from post hoc discussions. This information is elicited and structured using the probe questions defined by O'Hare *et al.* (2000) (table 3). A subject matter expert was interviewed and CDM analyses were conducted for the air threat scenario, subsurface threat, and surface threat scenario (only the first of these three scenarios is presented here because of space limitations).

3.2. *Extract knowledge objects*

In order to convert the CDM tables into propositions, a content analysis is performed. In the first stage, this simply means separating all content words from any function words. For example, in response to one of the CDM probes, the SME answer that 'The process is scripted but the situation determines the plan, e.g. the nature of threat, degree of intelligence available, climatic conditions' would be reduced to the following knowledge objects: 'threat', 'intelligence', and 'weather'. Working through the table leads to a set of

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Table 3. Critical decision method probes.

Goal specification	What were your specific goals at the various decision points?
Cue identification	What features were you looking for when you formulated your decision?
	How did you know that you needed to make the decision?
	How did you know when to make the decision?
Expectancy	Were you expecting to make this sort of decision during the course of the event?
	Describe how this affected your decision-making process
Conceptual	Are there any situations in which your decision would have turned out differently?
	Describe the nature of these situations and the characteristics that would have changed the outcome of your decision
Influence of uncertainty	At any stage, were you uncertain about either the reliability or the relevance of the information that you had available?
	At any stage, were you uncertain about the appropriateness of the decision?
Information integration	What was the most important piece of information that you used to formulate the decision?
Situation awareness	What information did you have available to you at the time of the decision?
Situation assessment	Did you use all the information available to you when formulating the decision?
	Was there any additional information that you might have used to assist in the formulation of the decision?
Options	Were there any other alternatives available to you other than the decision you made?
Decision blocking: stress	Was there any stage during the decision-making process in which you found it difficult to process and integrate the information available?
	Describe precisely the nature of the situation
Basis of choice	Do you think that you could develop a rule, based on your experience, which could assist another person to make the same decision successfully?
	Why/Why not?
Analogy/generalization	Were you, at any time, reminded of previous experiences in which a similar decision was made?
	Were you, at any time, reminded of previous experiences in which a different decision was made?

Source: O'Hare *et al.* (2000).

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knowledge objects. These are checked to ensure that duplication is minimized and are then used to construct the propositional network.

In our interpretation of these activities we identify a network of knowledge objects. We have defined knowledge objects as the entities in the world that people detect, classify, and manipulate. For example, knowledge objects would comprise knowledge of own and enemy land, air, and sea assets (and the capabilities of these assets), targets, priorities, radar bandwidths, plans, and strategies. There are potential knowledge objects for every set of phenomena in the world. In this way we have interpreted the battle space as a network of knowledge objects rather than a technological network. This is not to deny the importance of the technological network, but to state that it is the correct activation of the knowledge network which ensures that the whole system performs effectively.

The idea that 'knowledge' can be represented in the form of a network has been a major source of discussion of memory in cognitive psychology since the 1970s. Initially, researchers used semantic nets as a way of representing the association between items within a concept. Such an approach gave rise to theoretical insights such as spreading activation (Quillian 1969, Collins and Loftus 1975). The basic premise is that an item of knowledge will be easier to process if it has a high level of activation. According to Collins and Loftus (1975), other nodes linked to this active node also become activated, i.e. 'The spread of activation constantly expands, first to all the nodes linked to the first node, then to all the nodes linked to each of these nodes, and so on' (Collins and Loftus 1975, p. 408). One way of considering a semantic network is that it is like the 'concept mapping' idea, i.e. one writes a single word in a box and then creates more boxes which link to this initial word.

3.3. *Represent the relations between knowledge objects and their activation*

Propositional networks are like semantic networks in that they contain nodes (with words) and links between nodes, but differ in two ways. First, the words are not necessarily randomly added to the network but involve the definition of propositions. A proposition is a basic statement, i.e. 'the smallest unit about which it makes sense to make the judgement true or false' (Anderson 1980, p. 102). Secondly, the links between words are labelled to define the relationship between propositions. These relations might be in terms of subject and object (in grammatical terms), with a corresponding relation term. On the basis of such descriptions, it is possible to claim that one can produce dictionary-like definitions of concepts through the application of basic propositions and operators (Ogden 1987).

From the propositions derived through content analysis from the CDM tables, it is possible to construct an initial propositional network to show the knowledge that is related to this incident. The propositional network consists of a set of nodes which represent objects, for example sources of information, agents, etc. that are linked through specific operators. From this network, it should be possible to identify required information and possible options relevant to this incident.

In the initial descriptions, the operators are simple relations such as 'causes', 'knows', 'has', and 'is'. Thus the example knowledge objects 'platform', 'intent', 'weapons', and 'threat' would be represented as shown in figure 4.

The justification for using a propositional network in this manner is that it represents the 'ideal' collection of knowledge for a mission (and is probably best constructed post hoc). As the incident unfolds, so participants will have access to more of this knowledge (either through communication with other agents or through recognizing changes in the incident status). An advantage of producing such a diagram is that, through use of colour coding, it is possible to indicate in a simple visual manner the relationship between specific agents and specific objects over the course of a mission. As the mission unfolds, so different nodes in this network will become active. The active nodes might be relevant only to one or two agents within the system. For example, the situation described began with planning resources and strategy. This would cause the nodes relating to <intelligence>, <platform>, <intent>, <weapons>, <scenarios>, <threat>, and <engage> to be active. As the mission progresses, so the activation of nodes alters. However, where there are jointly active nodes, it is necessary to ensure some level of communication across agents. The knowledge network provides a graphical representation of the ideas and forms

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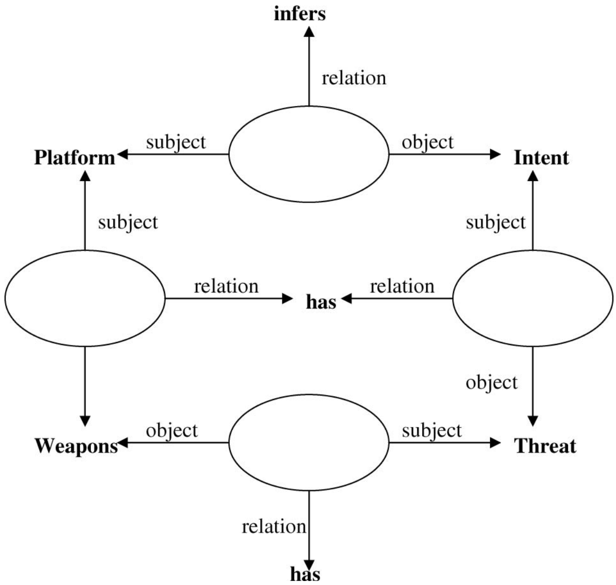

Figure 4. Propositional network for air, surface, and subsurface threat tasks.

the basis for a distributed theory of SA that is being developed from the work (Stanton *et al.* 2004a).

The complete knowledge network for the surface, subsurface and air threat tasks is shown in figure 5 (this figure was created using WESTT software (Houghton *et al.* 2005) for the construction of propositional networks). The total situation for the system under analysis is described by 64 knowledge objects. The knowledge network makes no reference to any particular job roles, and technology is only referred to in a general sense (e.g. weapons, satellite, radar, and sonar). While this is a general system-level representation, activation of any of the knowledge objects has been identified with particular tasks from the task network as shown in figures 6–12. As described in the task network analysis, the knowledge network illustrated in figure 6 is performed prior to the mission, and the knowledge networks illustrated in figures 7–12 are performed concurrently by different parts of the team and technological system. This activation of the knowledge network illustrates the distributed situation awareness of the system in a very literal sense.

Figure 6 shows the knowledge objects activated in the planning of resources and strategy. Figure 7 shows the knowledge objects activated in the identification and classification of targets. Figure 8 shows the knowledge objects activated in the assessment of threat and the allocation of weapons and assets to targets. Figure 9 shows the knowledge objects activated in the engagement of targets. Figure 10 shows the knowledge objects activated in the reassessment of target engagement success and the reallocation of weapons and assets to new targets. Figure 11 shows the knowledge objects activated in the control of external resources. Figure 12 shows the knowledge objects activated in the posturing of the platform for attack. These data are derived from the CDMs and HTA as described earlier and were validated by subject matter experts. Analysis of the knowledge object activated by each phase was conducted and is presented after the figures.

From this analysis, it is possible to identify the key knowledge objects that have salience to each phase of operation. For the purpose of this analysis, salience is defined as

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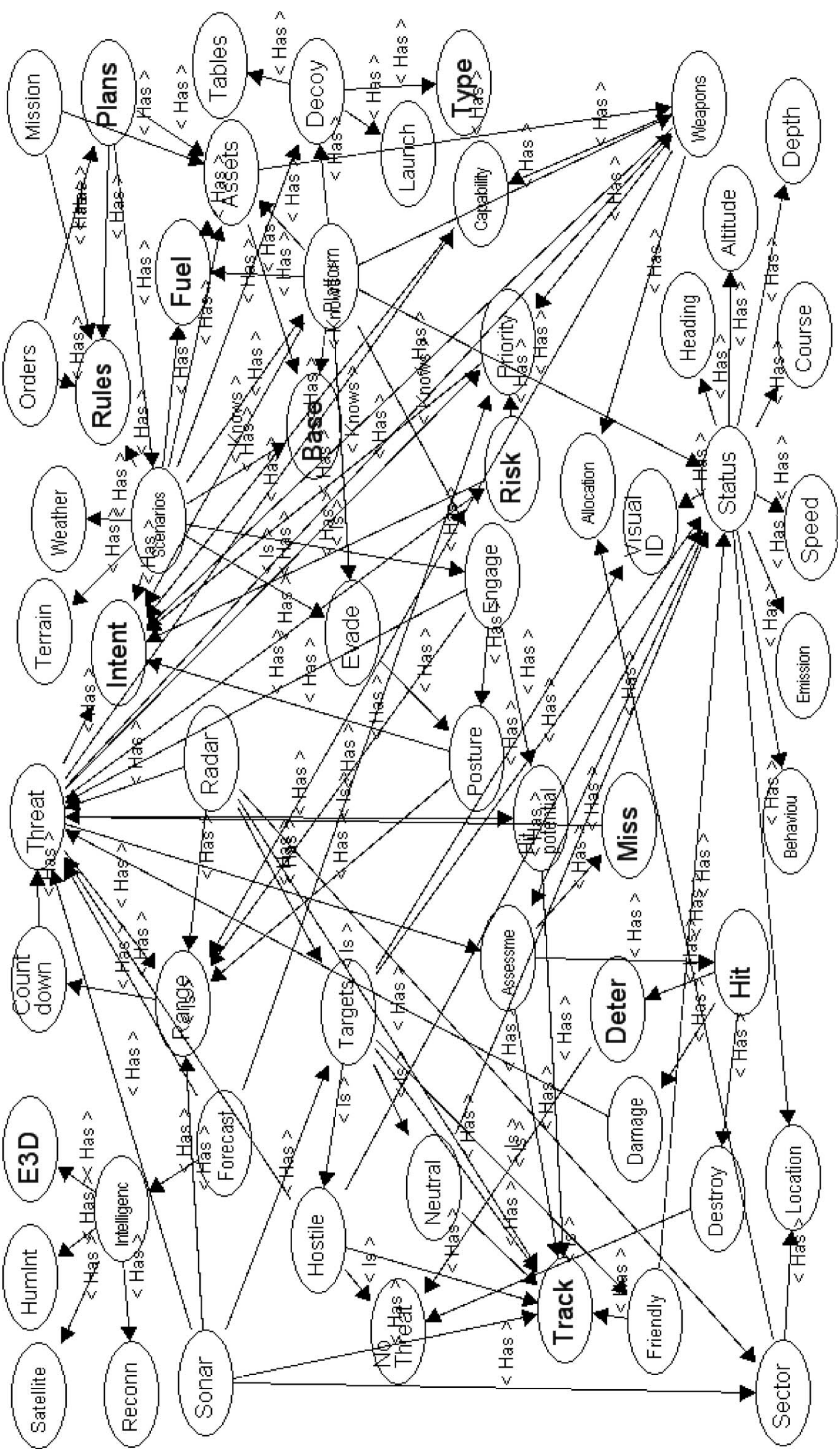

Figure 5. Propositional network for air, surface, and subsurface threat tasks.

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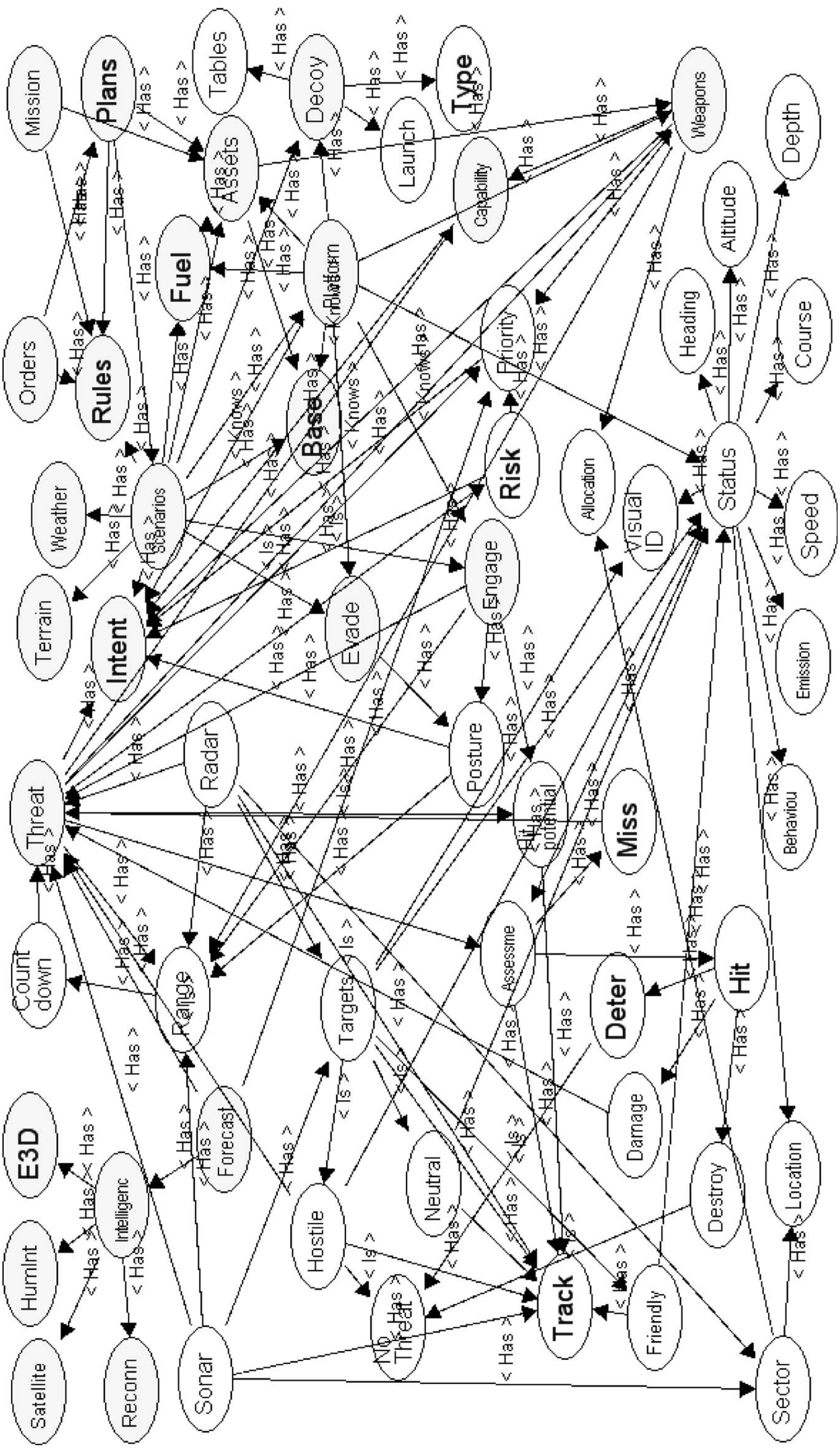

Figure 6. Propositional network for planning resources and strategy.

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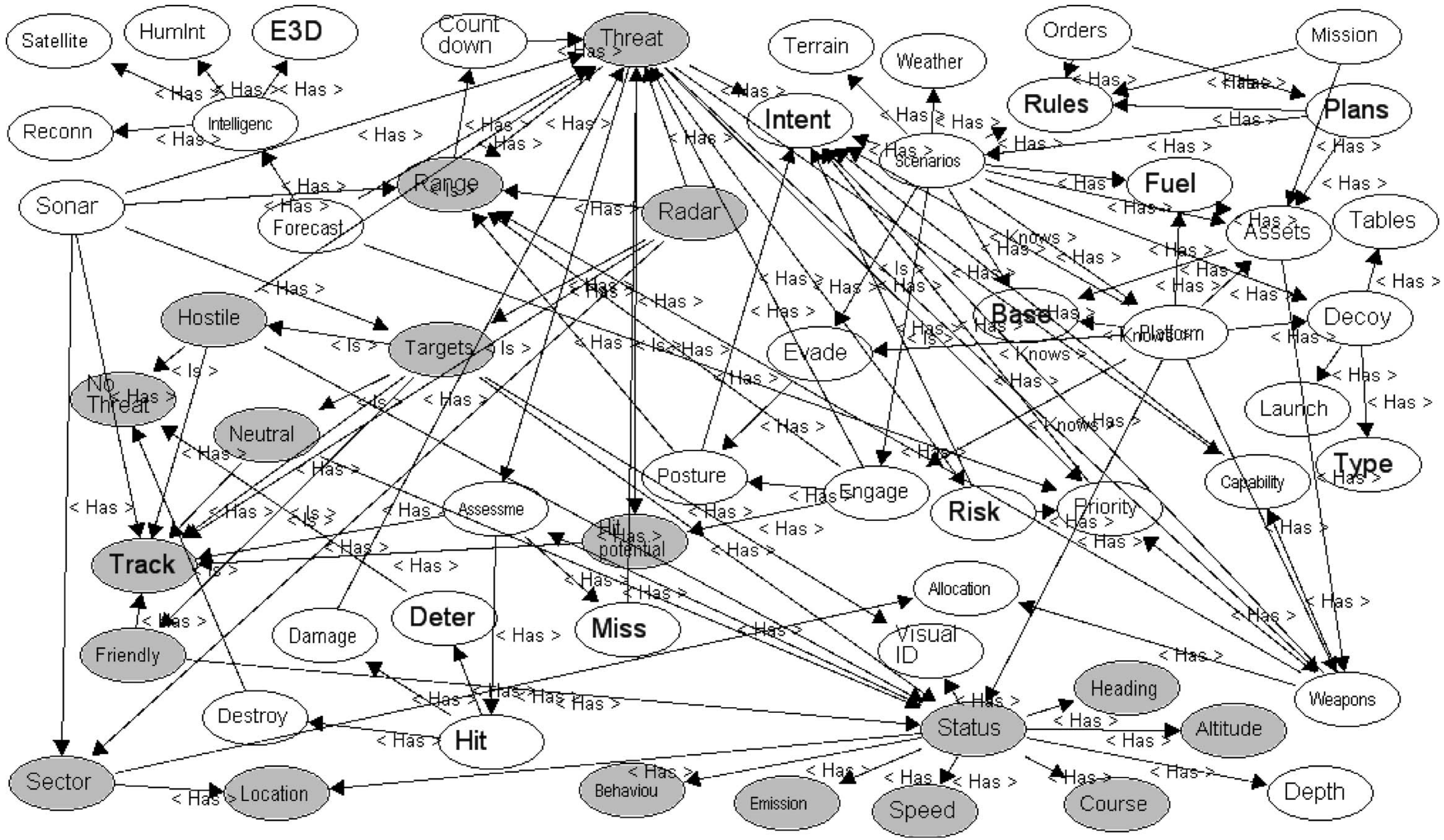

Figure 7. Propositional network for identifying and classifying targets.

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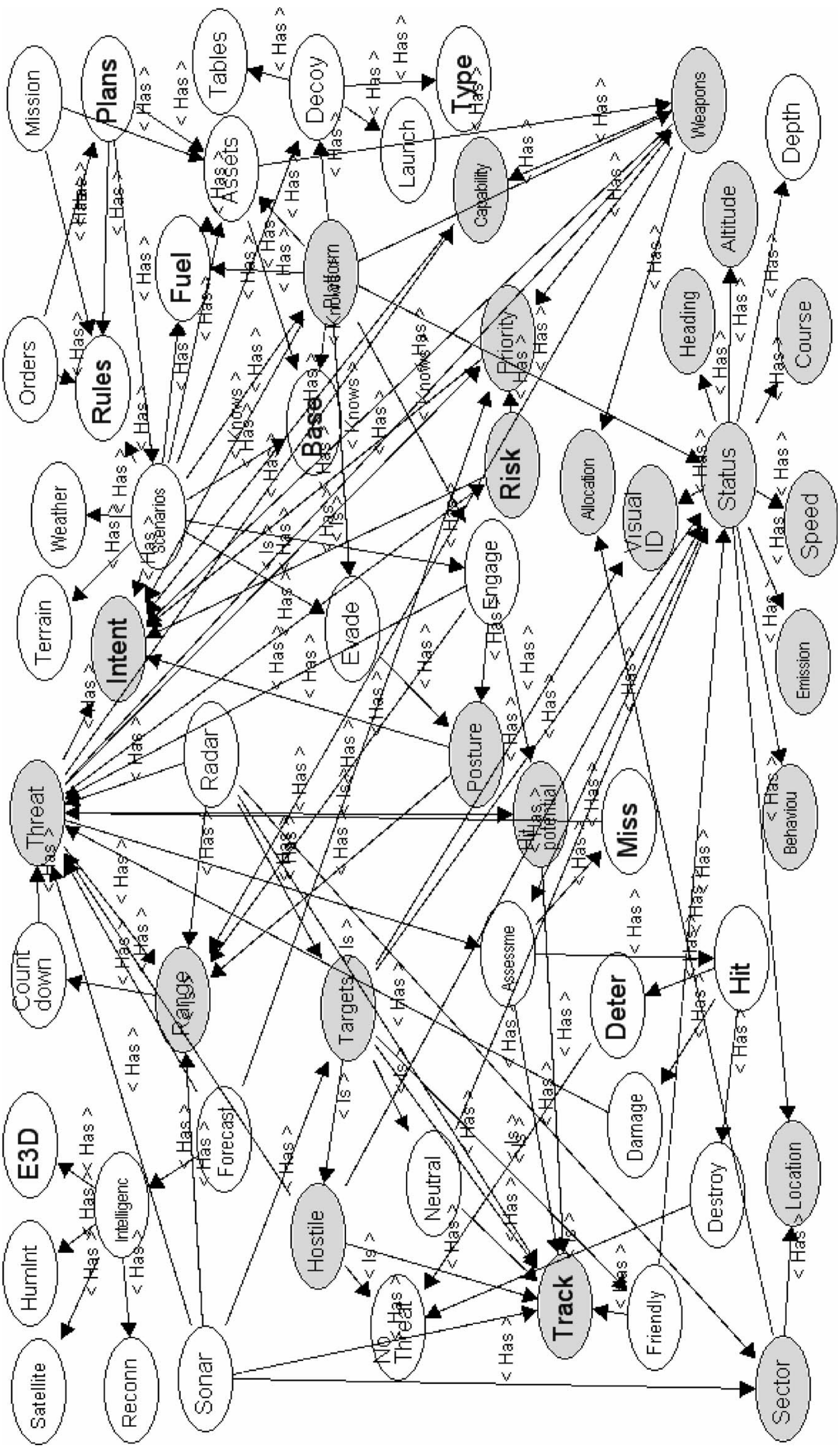

Figure 8. Propositional network for assessing threat and allocating targets.

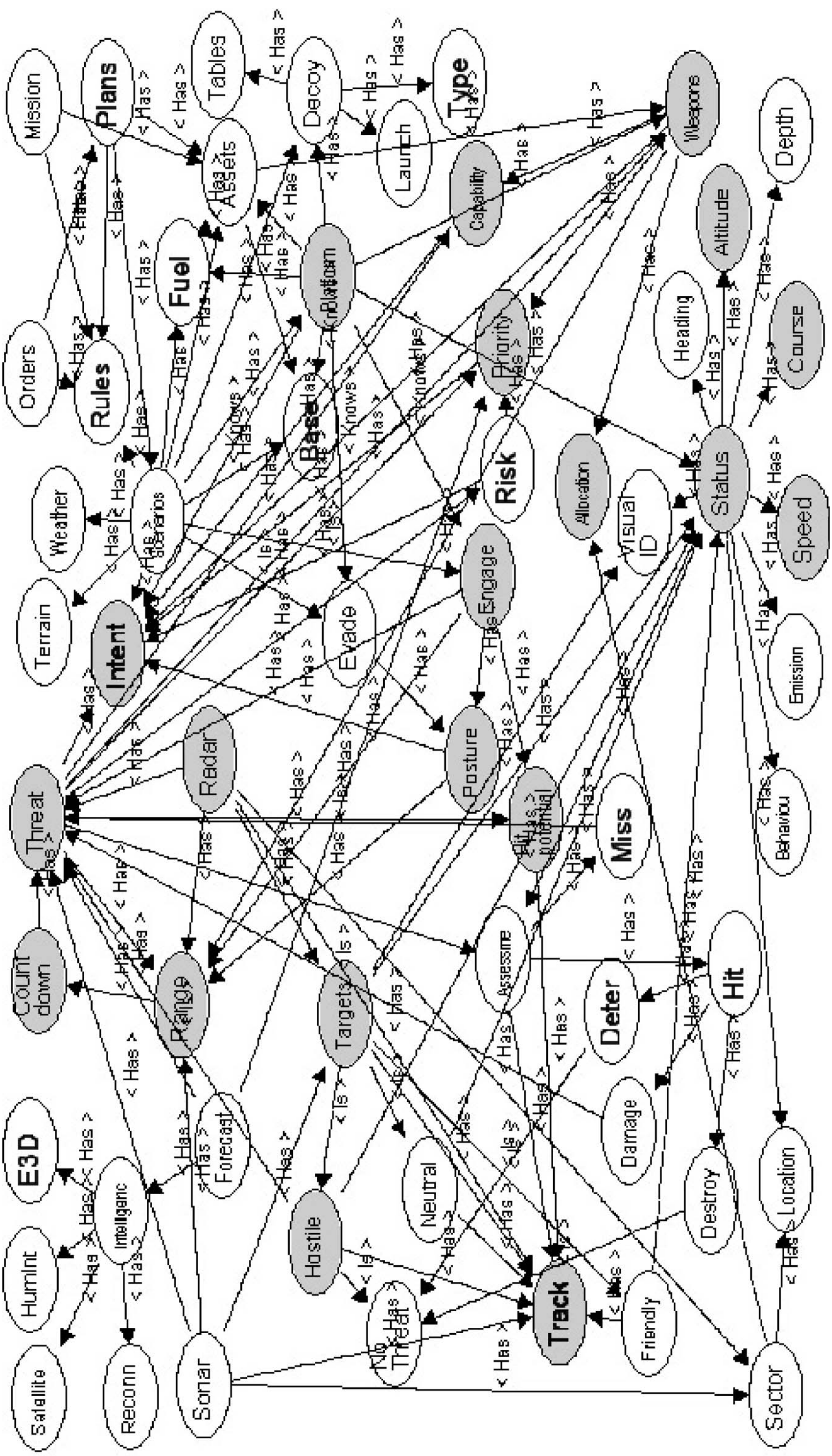

Figure 9. Propositional network for engaging targets.

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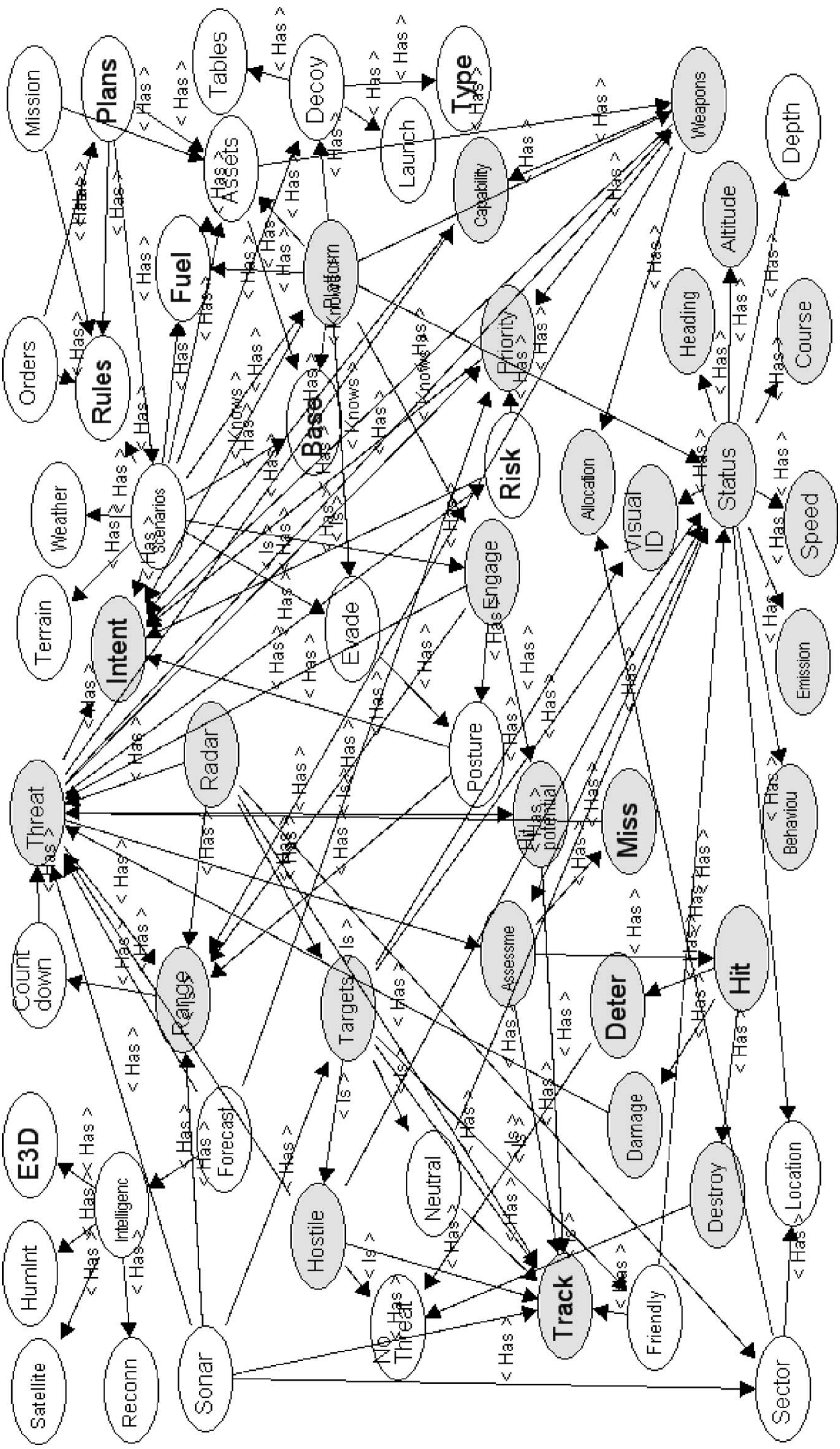

Figure 10. Propositional network for reassessing targets and allocating weapons to new targets.

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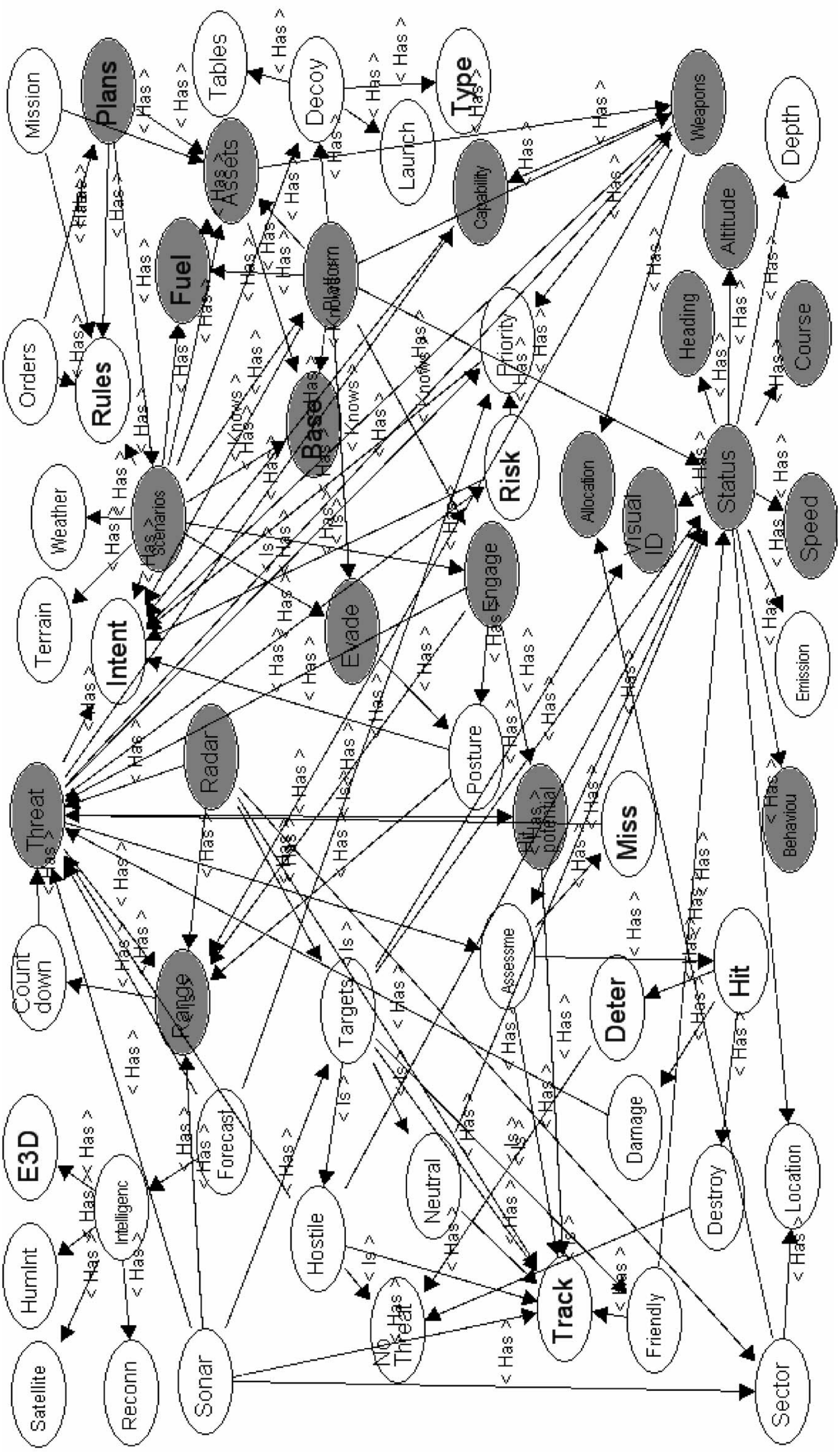

Figure 11. Propositional network for controlling external resources.

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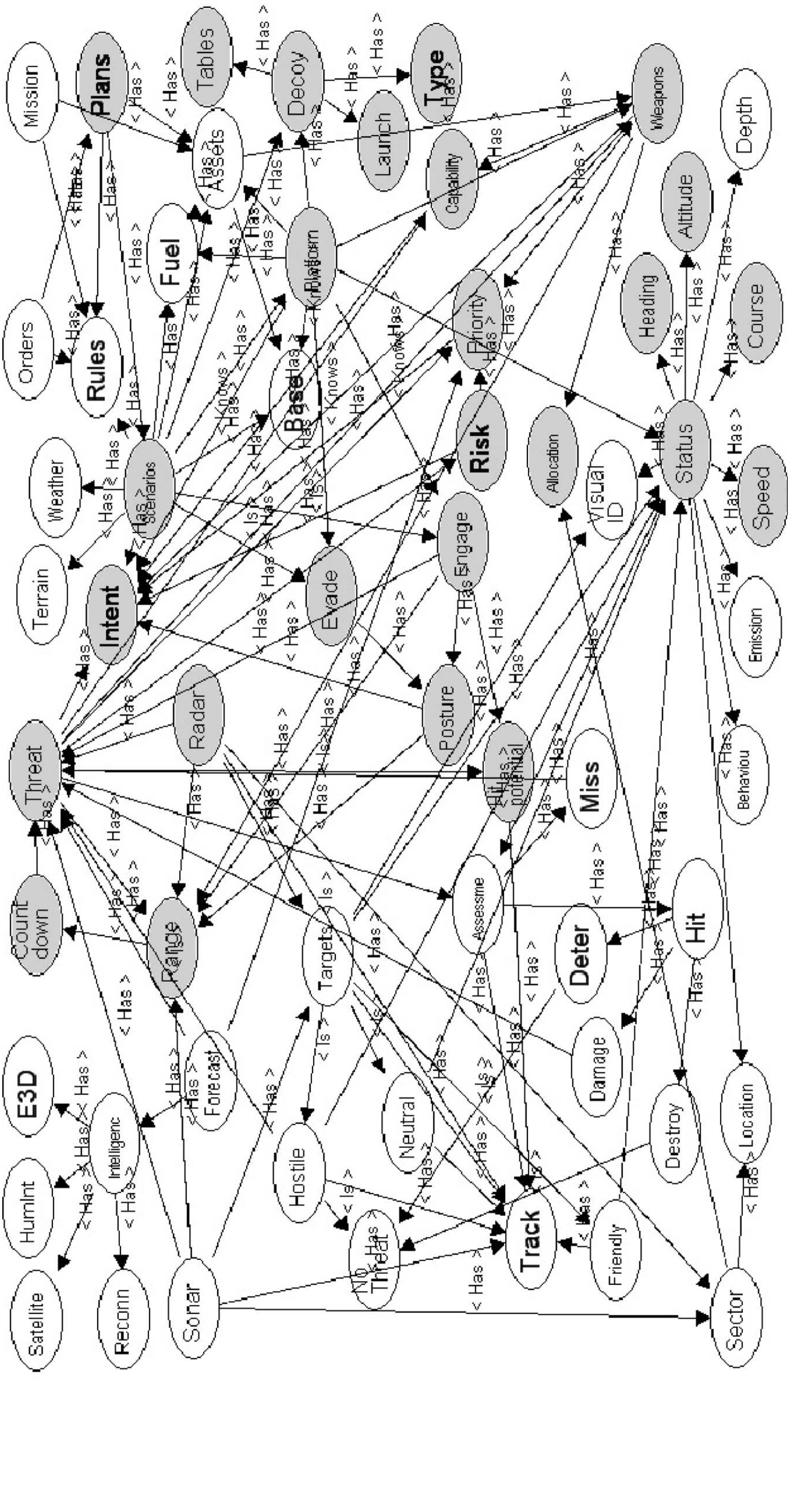

Figure 12. Propositional network for posturing platform for attack.

those knowledge objects that serve as a central hub to other knowledge objects (i.e. have five or more links to other knowledge objects). This criterion produces a list of 12 knowledge objects from a pool of 64 (approximately one-fifth of the total number of knowledge objects). The objects are intent, weapons, scenarios, threat, range, engage, radar, targets, status, intelligence, platform, and hit potential. The purpose of this analysis is to identify knowledge objects that play a central role in the threat tasks. Each of these core knowledge objects is represented in a generic table against each stage for the purpose of highlighting its role.

As table 3 shows, different core knowledge objects are salient at different points in the operation (e.g. intent is relevant at the plan, allocate, engage, reassess and posture phases, whereas intelligence is relevant only in the plan phase). The passing of knowledge objects from one phase to another involves some manipulation of the object before it is passed and then some means of communicating the nature of the object (e.g. the priority of targets is assessed before weapon systems are allocated to them and then they may be engaged), either implicitly or explicitly.

The purpose of this analysis is that it brings all three representations together, namely the social network (i.e. whom is communicating with whom), the task network (i.e. the goals of what is being done), and the knowledge network (i.e. the key features of SA for each phase of operation). The HMS Dryad Type 23 operations control room studies showed highly complex interactions between crew and communication channels. It is an extremely intense environment and over a relatively short period of time (approximately 2 hours) an enormous amount of communication occurred with information being transferred.

The methods indicate that a great deal of teamwork is occurring in each scenario although there is a clear hierarchy. The PWO and AAWO still remain the central nodes of the operations room. Information is shared between the crew members however the majority of this information seems to be shared via the PWO and AAWO.

Shared awareness can be seen from the analysis in table 4. Many of the knowledge objects are shared within the three individual scenarios (i.e. air, surface, and subsurface) as well as across the whole mission. It is important to remember that the three scenarios observed will often happen at the same time and will not be separated into three clear

Table 4. Analysis of core knowledge objects within the seven phases of operation.

Knowledge objects	Plan task	Identify task	Allocate task	Engage task	Reassess task	Control task	Posture task
Intent	■		■	■	■		■
Weapons	■		■	■	■	■	■
Scenarios	■					■	■
Threat	■	■	■	■	■	■	■
Range		■	■	■	■	■	■
Engage	■			■		■	■
Radar				■		■	■
Targets		■	■	■	■		
Status		■	■	■	■	■	■
Intelligence	■						
Platform	■		■	■	■	■	■
Hit potential		■	■	■	■	■	■
Count of knowledge objects	7/12	5/12	8/12	10/12	8/12	9/12	10/12

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areas. Thus the sharing of knowledge objects across scenarios will be essential for effective operations.

There is the implication that DSA could be viewed in terms of the activated knowledge objects, and these activations change over the course or phases of a mission. This has implications for workload and levels of uncertainty. We speculate that the workload and uncertainty might increase with the number of knowledge objects that need to be managed. Workload might simply increase because there is more knowledge to manage whereas uncertainty might increase because there are more things to keep track of. This hypothesis requires further empirical investigation. The results of this application of the methodology are intended to form a part of wider data collection and analysis with a view to developing a generic model of command and control.

Now that the network models have been defined, it should be possible to consider the potential effects of changes in those networks. As mentioned in the introduction to this paper, these questions include addressing the effects of changing the task, social, or propositional networks and the subsequent effects on DSA, workload, error rates, timeliness of response, and overall mission effectiveness. This will be the focus of our subsequent research.

4. Conclusions

The idea that there exists a network of knowledge objects for the entire system raises some interesting points about shared awareness. First, we claim that it is the system as a whole, rather than a given individual, that holds all relevant knowledge; individuals have different views of this network. Secondly, the view that an individual has must be sufficient to support the activity that he/she performs, i.e. command activity requires high-level awareness of a wide range of knowledge objects, whereas target tracking requires low-level detailed awareness of a subset of knowledge objects. Third 'sharing' awareness does not necessarily entail communication between individuals; it might be confusing or misleading if all individuals attempted to share all their separate views of the situation. Rather, it is important for the agents within a system to have awareness of who is likely to hold specific views and, consequently, to interpret the potential usefulness of information that can be passed through the network in terms of these views. Extending the DSA to Endsley's conception of SA would mean that some individuals are engaged in perception tasks (such as the picture compilers and picture supervisors), some are engaged in comprehension and in the projection tasks (such as the anti-air warfare officer and the principle warfare officer) and other are engaged in the response execution tasks (such as the missile directors and the electronic warfare director). Thus, referring back to the DSA analysis of the fire-fighting system, we argue that the theory and method work equally well with single-person–machine systems as well as with large multi-person–machine systems, as DSA is concerned with how knowledge is used and parsed between agents in systems interaction.

Indeed, this latter point may even hold the key to DSA. Assuming that performance will be most effective when there is 'good' DSA throughout the system as a whole, it follows that the network links are more crucial than the nodes themselves in maintaining DSA. Moreover, there are then two aspects of SA at any given node: individual SA of one's own task, and a 'meta-SA' of the whole system's DSA. Given that effective team-working depends on information transfer across the network links, knowing which links to use (and where to offer information when needed) will really determine the quality of DSA, and thus is perhaps the truest description of DSA itself.

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The distributed cognition approach has been successfully used to analyse the cognitive properties of a variety of environments (Perry 2003), adding to our understanding of the cognitive processes that are taking place over and above information gleaned from studies concentrating solely on individual cognition (Flor and Hutchins 1991). It has also highlighted a new level of study for other research areas, including DSA. The DSA approach does not dispute that the individuals in the system will have their own awareness of a situation, or that groups of individuals may share some level of understanding of the situation (Artman and Garbis 1998). It is asserted that complex problem-solving systems will have their own cognitive properties (including SA) which cannot be accounted for by individual cognition and that to study a system at the level of the individual will fail to pick up on these systems-level features (Hutchins 1995, Perry 2003).

The knowledge and task networks shown in figures 5–12 are based on observational data and provide us with model exemplars of DSA for specific tasks in this environment. These could be used to diagnose problems in system performance where such problems are attributed to failures in DSA. Taking the models one step further, it may even be possible to use the networks in a predictive fashion to run simulations of different task structures. Therefore the DSA approach has implications for the design of the working environment (e.g. in terms of team structure), which can impact the flow of information through the system, and for human–computer inteactions, because of the importance of technological artefacts in distributed environments (Artman 2000).

By viewing SA first as a systems-level phenomenon, it is possible to identify the aspects of a situation about which agents require knowledge. By viewing the active knowledge in each state of an incident, it is possible to determine who knows what at a given time. From this perspective, it becomes possible to indicate how information needs to disseminate through the system for effective performance and to identify possible barriers to effective dissemination. One of the keys to effective DSA is links, since it is not possible to have DSA without communication. The graphical representation provides a simple but effective means by which system SA can be mapped. From this work we further propose that adding additional communications requirements (through which agents share or communicate their mental models) can add significant burden to the processes and may actually impede SA by introducing tasks that might serve to activate additional but unnecessary nodes in the network, introducing time delays between receiving and acting upon information, and inappropriate emphasis on some links in the network. The challenge at present is to continue to collect evidence that will enable us to substantiate this theory. In particular, our work focuses on the question of how best to describe SA at a system's level and how communication between agents within a system can support effective performance.

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